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SOME ASPECTS OF ANTIPROTON–NUCLEUS PHYSICS[1]

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Abstract

A brief review of antiproton–nucleus physics is presented. Some topics are related to early LEAR experiments, and others to more recent measurements or proposals. These include: exotic molecules, elastic and inelastic scattering, deep annihilation, strangeness production, neutron–antineutron oscillations, halo nuclei, antiproton production in nuclear reactions etc.

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1 Introduction

There are many motivations for studying the antinucleon–nucleus ($\overline{\text{N}}$A) interaction. This is first a tool for improving our empirical knowledge of the "elementary" nucleon–antinucleon (N$\overline{\text{N}}$) process, since 2-body scattering cannot yet be studied for all spin and isospin configurations that are needed for a full reconstruction of the 2-body amplitude.

Conversely, once the behaviour of an antinucleon in ordinary matter is known, $\overline{\text{N}}$A experiments can probe some aspects of the nucleus: equation of state in a regime of unusual excitation, neutron skin, etc.

Hopefully, $\overline{\text{N}}$A physics is not restricted to a straightforward folding of the elementary N$\overline{\text{N}}$ scattering and annihilation with wave functions of nuclei. New phenomena are looked for, such as annihilation on several nucleons, increase of strangeness production, formation of hot bubbles inside a nucleus, etc.

Remarkably, the physics topics related to $\overline{\text{N}}$A experiments involve different scales, ranging form several tens of fermis, the typical Bohr radius for antiprotons, to a fraction of fermi, the distance at which quark–antiquark annihilation takes place.

By no means, this review is intended to cover all aspects of $\overline{\text{N}}$A physics. We refer the reader to other contributions, in particular on induced fission[1] and Pontecorvo reactions [2].

2 Antiprotonic molecules

There is a renewed interest in antiprotonic atoms. As shown by Yamazaki at this Conference[3], the Coulomb forces generate metastable states of systems with a nucleus, an antiproton, and some electrons. There is already an abundant literature on the subject[4]. Our attention was previously restricted to Rydberg-like atomic states of an antiproton around a nucleus, the electrons either being expelled or orbiting far away.

This is a good opportunity to recall that many atomic or molecular states can be made by combining antiprotons with ordinary nuclei. For instance, the configurations

$$(\bar{\text{p}}\text{pp}), \qquad (\bar{\text{p}}\text{dt}), \qquad (\bar{\text{p}}\bar{\text{p}}\text{pp}), \quad \ldots \tag{1}$$

have their ground state which is stable against dissociation in smaller clusters[5, 6]. Some of these exotic states seemingly belong to the domain of science fiction. One should remember, however, that positron or muon chemistry, once at a rather primitive stage, is nowadays dealing with rather complex systems.

3 Antiprotonic atoms and elastic scattering

The data on elastic scattering and the energy shifts of antiprotonic atoms have been successfully analyzed in terms of optical $\overline{\text{N}}$A potentials. Simple empirical potentials,

typically of Wood–Saxon type, have been tuned to reproduce the data. A moderately attractive real part is favoured, to supplement the absorptive component. The optical potential has also been derived by KMT[7, 8] type of folding of the elementary $N\overline{N}$ amplitude. The resulting real potential is usually repulsive inside the nucleus, but it becomes attractive near the surface, in the region which is actually probed by low-energy scattering or in $\bar{p}$-atoms. Elaborate medium corrections have been worked out, but they do not change the picture too dramatically, as long as the antinucleon interacts at the surface.

Microscopic calculations reproduce fairly well the spatial extension that is needed to fit the data. While the imaginary potential does not exceed much the border of the nuclear density, the real attraction extends a little outside the nucleus.

4   Inelastic scattering

"Inelastic" is understood here as in nuclear physics. Namely one considers a reaction

$$\overline{N} + A \rightarrow \overline{N} + A'. \tag{2}$$

This includes charge-exchange processes. The precise identification of the new nucleus or nuclear level A', with known properties, allows one to filter the quantum numbers which are transferred from the antinucleon to the nucleus, i.e., to focus on selected spin and isospin components of the potential. Extended studies, in particular by Dover and collaborators[9], have shown that this is potentially a very powerful tool to determine the key characteristics of the $N\overline{N}$ force, and to check current ideas on the excitation of nuclear levels. Preliminary experimental investigations by the PS 184 collaboration at LEAR[9] were not accurate enough to provide definite conclusions, and this program has not been resumed with improved detectors, unfortunately.

The inclusive $(\bar{p}, p)$ reaction was also examined, in a search for possible $\overline{N}A$ bound states. These states would generalize the $N\overline{N}$ bound states or resonances, which were looked for in $N\overline{N}$ scattering and annihilation experiments. The results were negative[9].

5   Integrated aspects of annihilation

$\overline{N}A$ data confirm that $N\overline{N}$ annihilation is very strong. In particular, one needs a very deep absorptive component of the optical potential. In atoms, the hadronic width $\Im m\,E$ is comparable to the shift $\Re e\,E$ of the binding energy. We already mentioned the consequence that low-energy antiprotons do not penetrate much into the nuclear medium. Then comparing data on neighboring isotopes gives an indication on the isospin $I = 1$ component of the interaction, as the surface of heavier isotopes is likely to be dominated by neutrons.

An interesting result of $\overline{N}A$ experiments is that annihilation seems weaker for $I = 1$[10], i.e.,

$$\sigma_{\rm a}(I = 1) < \sigma_{\rm a}(I = 0). \tag{3}$$

Among the possible theoretical explanations, one may mention

i) There are less combinatorial possibilities of quark–antiquark annihilation in the case of $I = 1$.

ii) For a given intrinsic annihilation strength (for instance in a scenario where quark rearrangement would dominate), annihilation is less effective for $I = 1$ than for $I = 0$, since the real part of the potential is less attractive, at least in models based on meson exchanges. According to Shapiro[11], annihilation is monitored by the real potential, which focuses the wave function toward the short-distance region.

Some results on the isospin dependence are based on Deuterium or Helium data, by comparing the number of $(\bar{p}n)$ annihilation events to that of $(\bar{p}p)$. In principle, a detailed 3-body or 4-body calculations could be carried out, with phenomenological $N\overline{N}$ potentials.

6 Specific aspects of annihilation

A recurrent and interesting topics is the so-called $B > 0$ contribution to annihilation, or annihilation on several nucleons. This means processes which cannot be reduced to an ordinary $N\overline{N}$ annihilation followed by rescattering of the annihilation products. This is discussed in talks on Pontecorvo reactions or strangeness production.

Another classic deals with deep annihilation. Higher-energy $\bar{p}$, those for instance of the SuperLEAR proposal[12, 13], have a smaller cross section, and thus penetrate more deeply into the nucleus. Moreover, the Lorentz boost focuses the mesons resulting from the primary annihilation in the forward direction, where they hardly escape rescattering. Hence a large energy can be deposited in the nucleus, without the compression that is experienced in heavy-ion collisions of comparable energy release. Annihilation of medium-energy antiprotons would never produce a quark–gluon plasma, but new types of excited nuclei are sometimes formed, which probe new sectors of the equation of state.

At this Conference, however, the fashion is seemingly going backward, with more contributions on low-energy than high-energy annihilation. In particular, fission induced by $\bar{p}$ has been studied by several groups, with sophisticated detectors. As explained by von Egidy[1], a typical scenario is the following:

- annihilation at the surface, some fast pions or protons being emitted.

- particle evaporation of the compound nucleus (remember that in this field, "particle" means a nucleon or a small nucleus)

- binary (sometimes ternary) fission of the compound nucleus

- particle evaporation of the fission fragments, etc.

Again, the main interest lies in the comparison with what is observed in heavy-ion collisions.

7 Cold annihilation

There is a renewed interest in nuclear physics for nuclei with a neutron halo. In the simplest case, we have a compact core with $(A - 1)$ nucleons, and a Ath nucleon, usually a neutron, with a very small energy E. At large distances, the wave function behaves like

$$\Psi(\vec{r}) \sim \exp(-kr), \qquad k = \left(-\frac{2mE}{\hbar^2}\right)^{1/2}. \tag{4}$$

Estimates give a r.m.s. neutron radius exceeding that of the proton distribution by typically $0.5\,\text{fm}$. In the tail, the neutron density $\varrho_{\text{n}}(r)$ can overcome the proton one, $\varrho_{\text{p}}(r)$, by several orders of magnitude. Kaons have been used to probe this neutron skin. Antiprotons offer a viable alternative[2], due to their large cross-section. In favorable circumstances, annihilation can take place on a neutron at large distance from the core, so that a cold $(A - 1)$ nucleus is emitted. There is a proposal for studying such reactions at LEAR[14].

Even more interesting are the nuclei with two neutrons in the halo, say $(\alpha, \text{n}, \text{n})$, where α denotes the core. Sometimes, one observes the amazing property that $(\alpha, \text{n}, \text{n})$ is stable, while neither (α, n) nor (n, n) is stable. The simplest case is ^6He, i.e., $\alpha = (\text{ppnn})$. Such nuclei are called "Borromean", after the Borromean rings which are interlaced in such a subtle topological way that if any one of them is removed, the other two become unlocked. Borromean binding does not require 3-body forces, and shows up in simple Hamiltonian models[15]. If for instance one considers bosons interacting through the Yukawa interaction $-\text{g}\sum_{i<j}\exp(-\mu r_{ij})/r_{ij}$, the critical coupling g_3 for binding three particles is around 20% lower than the critical coupling g_2 for 2-body binding. The wave function of such nuclear systems is very extended, so if a low-energy antiproton comes in, one could observe a final state

$$n + \alpha + (\bar{\text{p}}\text{n} \to \text{mesons}). \tag{5}$$

8 Neutron–antineutron oscillations

Proton decay has been predicted in early unified theories of electroweak and strong interactions, but has never been seen in underground experiments. Some alternative theories predict neutron–antineutron oscillations ($\text{n} \leftrightarrow \bar{\text{n}}$). A direct, but difficult measurements of $\text{n} \leftrightarrow \bar{\text{n}}$ makes use of high-intensity neutron beams. An indirect bound on $\text{n} \leftrightarrow \bar{\text{n}}$ is provided by proton-decay experiments, since the detectors use nuclei (^{16}O, ^{40}Ca, etc.) rather than Hydrogen. The stability of these nuclei implies that the protons do not disintegrate, and also that the neutrons are not transformed into antineutrons. Several groups have calculated that the present limit $T > 10^{31}$

years on the stability of matter implies a limit $\tau > 10^8\,$s on the period of n $\leftrightarrow$ n̄. This calculation is rather safe, since it mostly uses the $\overline{\mathrm{N}}$A optical potential near the surface of nuclei, i.e., precisely in the region where it has been measured in LEAR experiments. There is a recent claim[16] that the bound $\tau > 10^8\,$s should be revised by 31 orders of magnitude, but it turns out that this new calculation contains an error[17].

The behaviour of an antinucleon in the nuclear medium is also probed in more realistic experiments, namely antiproton production in nuclear collisions[18].

9 Conclusions

Many results on $\overline{\mathrm{N}}$A have been obtained at LEAR and elsewhere, but the field is far from being exhausted. Several new experiments could be done at moderate cost, if the antiproton source remains in operation at CERN. The considerations on medium-energy physics, as developed in the KAON or SuperLEAR study groups, remain fully valid. From the contributions and discussions at this conference, it is also clear that several astute experiments could be done with very cold antiprotons on selected targets. Radioactive nuclear beams are routinely obtained at ISOLDE facility of CERN, and there are new ideas for getting more neutron-rich ions. This is a theorist's dream to imagine collisions of antiprotons with such rare nuclei.

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